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Neutrino Dark Matter in the Higgs Triplet Model

SAHAR BAHRAMI AND MARIANA FRANK¹

*Department of Physics Concordia University 7141 Sherbrooke W,
Montreal, Quebec, Canada H4B 1R6*

We analyze the effects of introducing vector-like leptons in the Higgs Triplet Model providing the lightest vector-like neutrino as a Dark Matter candidate. We explore the effect of the relic density constraint on the mass and Yukawa coupling of dark matter, as well as calculate the cross sections for indirect and direct dark matter detection. We show our model predictions for the neutrino and muon fluxes from the Sun, and the restrictions they impose on the parameter space. We show that this model, with a restricted parameter space, is completely consistent with dark matter constraints, and indicate the resulting mass region for the dark matter.

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1 Introduction

We propose the Higgs Triplet Model (HTM) with vector-like leptons as a resolution to both neutrino masses and dark matter (DM) problems of the Standard Model (SM) [1]. The resolution to neutrino masses is through the known see-saw mechanism, using an additional Higgs triplet representation. The dark matter candidate is provided by a mostly singlet vector-like neutrino with small couplings to the Z boson. A new parity symmetry, under which all new vector-like leptons are odd, prohibits mixing with the ordinary SM leptons. Under this symmetry, the lightest odd particle becomes stable on cosmological timescales, and is consistent with the DM candidate of the universe. We analyze the consequences of this scenario by requiring agreement with the relic density and non-collider experimental data, particularly with direct searches for spin-independent (SI) or spin-dependent (SD) interactions with target nuclei, with indirect dark matter searches, as well as with ultra-high energy neutrino experiments.

2 The HTM with Vector-like Leptons

The Lagrangian density for this model contains, in addition to the usual HTM \mathcal{L}_{kin} , \mathcal{L}_Y and $V(\Phi, \Delta)$ terms for kinetic, Yukawa interaction for ordinary leptons, and potential terms, Yukawa interaction terms for the vector-like leptons \mathcal{L}_{VL} [1]:

$$\mathcal{L}_{\text{HTM}} = \mathcal{L}_{\text{kin}} + \mathcal{L}_Y + \mathcal{L}_{\text{VL}} - V(\Phi, \Delta). \quad (1)$$

The vector-like leptons in the model, with representations and quantum number are given in the Table below, and their interactions are given by \mathcal{L}_{VL} :

Name	\mathcal{L}'_L	\mathcal{L}''_R	e'_R	e''_L	ν'_R	ν''_L
Quantum Number	$(\mathbf{1}, \mathbf{2}, -1/2)$	$(\mathbf{1}, \mathbf{2}, -1/2)$	$(\mathbf{1}, \mathbf{1}, -1)$	$(\mathbf{1}, \mathbf{1}, -1)$	$(\mathbf{1}, \mathbf{1}, 0)$	$(\mathbf{1}, \mathbf{1}, 0)$

$$\begin{aligned} \mathcal{L}_{\text{VL}} = & -[M_L \bar{L}'_L L''_R + M_E \bar{e}'_R e''_L + M_\nu \bar{\nu}'_R \nu''_L + \frac{1}{2} M'_\nu \bar{\nu}'_R{}^c \nu'_R + \frac{1}{2} M''_\nu \bar{\nu}''_L{}^c \nu''_L + h'_E (\bar{L}'_L \Phi) e'_R \\ & + h''_E (\bar{L}''_R \Phi) e''_L + h'_\nu (\bar{L}'_L \tau \Phi^\dagger) \nu'_R + h''_\nu (\bar{L}''_R \tau \Phi^\dagger) \nu''_L + h'_{ij} \bar{L}'_L{}^c i \tau_2 \Delta L'_L + h''_{ij} \bar{L}''_R{}^c i \tau_2 \Delta L''_R \\ & + \lambda_E^i (\bar{L}'_L \Phi) e_R^i + \lambda_L^i (\bar{L}'_L \Phi) e_R^i + \lambda'_{ij} \bar{L}'_L{}^c i \tau_2 \Delta L'_L + \lambda''_{ij} \bar{L}''_R{}^c i \tau_2 \Delta L''_R + \text{h.c.}] \end{aligned} \quad (2)$$

Taking $h'_\nu \neq 0$, $M_\nu = 0$, but $h''_\nu = 0$, the lightest neutral eigenvalue provides a single DM candidate of mass M_{nu_1} and a single Yukawa coupling which are parameters we vary to obtain consistency with the experiment.

3 Dark Matter Relic Density

The relic density Ω_{DM} of non-baryonic DM in the energy-matter of the universe from cosmological data must be consistent with any model analyses. We calculate it,

restricted to 2σ allowed range $0.1144 \leq \Omega_{DM} h^2 \leq 0.1252$, as constrained by WMAP [2] and PLANCK [3] and present it below in Fig. 1, as a function of the DM mass and Yukawa coupling h'_ν . The two dips at $M_{DM} \sim 45$ GeV and ~ 62 GeV correspond to resonant annihilation into Z bosons and Higgs boson h . Relic density constraints restrict the dark matter mass to be heavier than 23 GeV and lighter than 103 GeV and independent of any other parameters, to which it is insensitive.

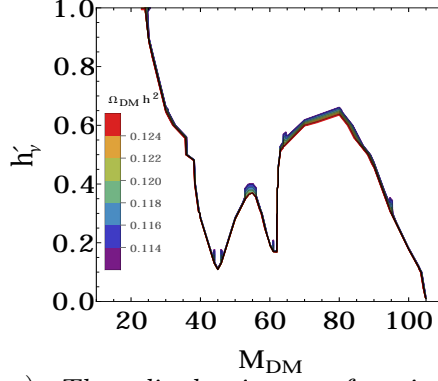


Figure 1: (color online). *The relic density as a function of M_{DM} (GeV) and h'_ν .*

4 Direct and Indirect Detection

Direct detection offers the opportunity to detect DM as it passes through and scatters off normal matter. The interaction can be classified as elastic or inelastic; and as spin-dependent or spin-independent. In spin-dependent scattering, the DM spin couples with the spin of the nucleon, while in spin-independent scattering, the cross section does not depend on spin.

Fig. 2, upper panel, shows the spin-dependent (SD) cross section of DM, as a function of the DM mass M_{DM} , whereas the bottom panel, shows the SD cross sections of the nucleon as contours in DM mass M_{DM} and Yukawa coupling h'_ν space. Left panels are for the proton, the right ones for the neutron. The red lines show points of the parameter space which reproduce acceptable relic density. The areas above the pink dashed line and green dashed-dotted line are ruled out by the COUPP and XENON100 [4, 5] measurements, respectively. The experimental results do not restrict the parameter space of the model, but only parameter points situated along the dash-dotted yellow lines in the bottom panels give the correct dark matter relic density.

In Fig. 3 we show the spin-independent (SI) cross section of nucleon, as a function of the DM mass M_{DM} (in GeV) (left panel), the spin-independent cross section of the proton as a graph in $M_{DM} - h'_\nu$ space, constrained by all the experiments with the exception of XENON100 (middle panel), and including XENON100 (with 2σ

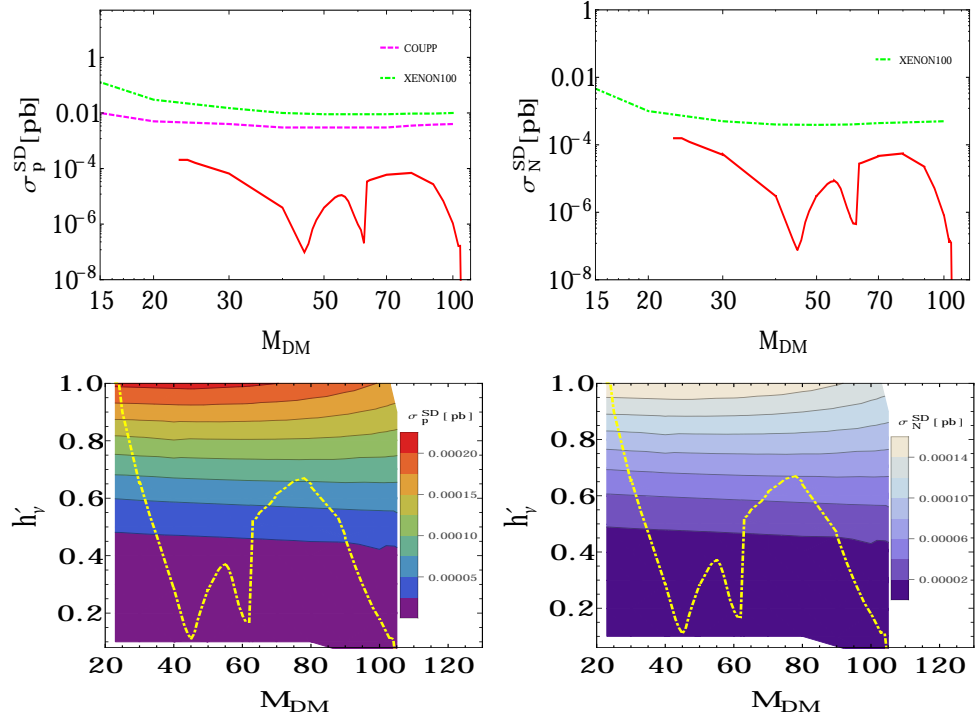


Figure 2: (color online). *SD* cross sections for proton (left) and neutron (right).

expected sensitivity) measurements (right panel). The red/dashed line includes all points yielding consistent relic density. The regions above the dash-dotted black line, dash-dotted green line, dash-dotted orange line, dash-dotted blue line, dash-dotted purple line, dash-dotted pink line are ruled out by XENON100 [6], XENON100 with 2σ expected sensitivity, CRESST-II [7], CDMS-II [8], TEXONO [9] and DAMIC100 (expected for 2014) [10] results, respectively. XENON100 results (with 2σ expected sensitivity) restrict the dark matter mass to be in the 37-52 GeV, or 57-63 GeV ranges, or heavier than 95 GeV, while white regions of parameter space are ruled out.

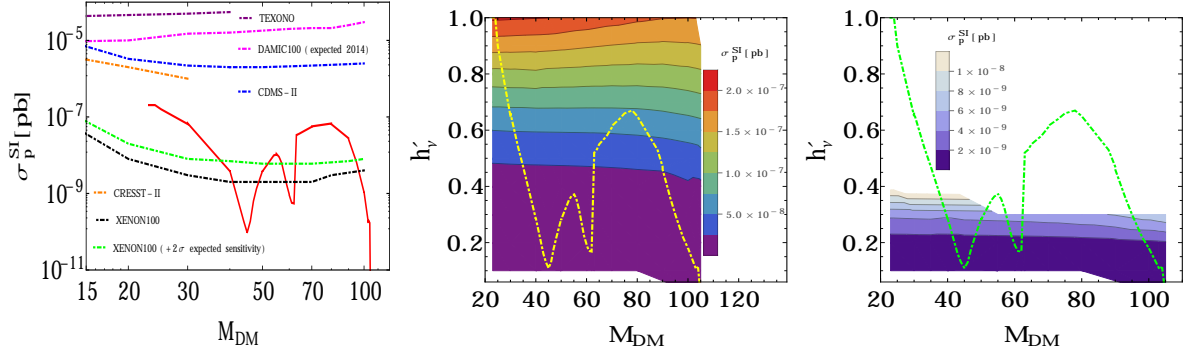


Figure 3: *SI* cross sections, with all constraints (left) without XENON100 (middle) and with XENON100 (right).

Indirect detection experiments for DM detection look for signatures of annihilations of DM particles in the flux of cosmic rays. In Fig. 4 we show the annihilation cross section of DM as a function of the DM mass M_{DM} , compared with Fermi-LAT Collaboration results [11] (left panel); (right panel) contour plot for the annihilation cross section in the $M_{DM} - h'_\nu$ plane. The contours are consisted with the experimental values for the cross sections, while the white regions are ruled out. Only points along the dash-dotted yellow line give the correct dark matter relic density to 2σ .

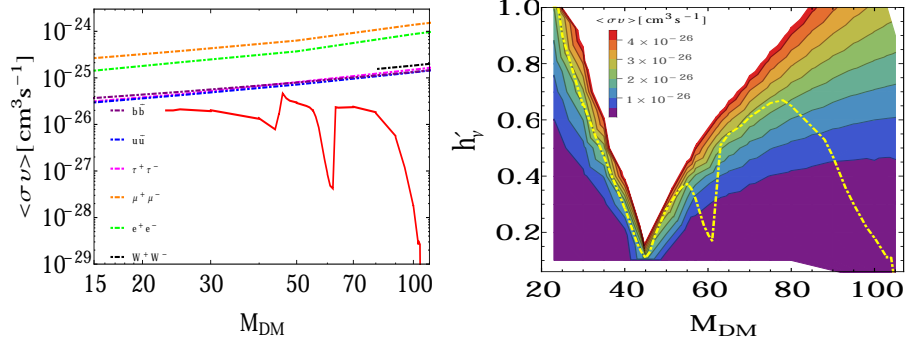


Figure 4: Annihilation cross section of DM.

Fig. 5 shows the neutrino (left panel) and muon (right panel) fluxes as functions of M_{DM} (in GeV). In the top graphs, our results are the red curve and the experimental results are from Baikal NT200 [12]. While the muon flux is consistent with all parameter points, the neutrino flux excludes M_{DM} in the 74-85 GeV region.

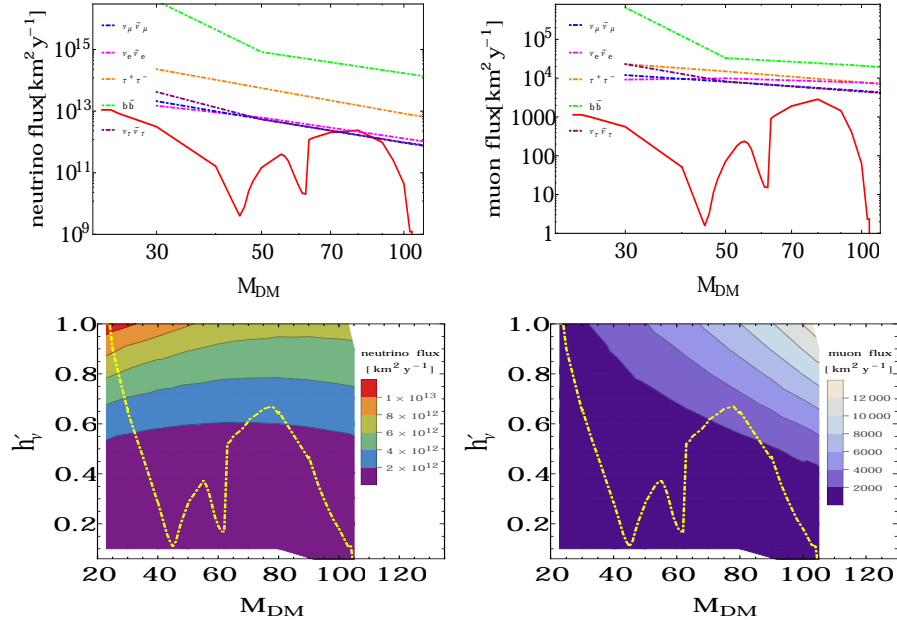


Figure 5: (color online). Fluxes of neutrinos (left panel) and muons (right panel).

5 Conclusion

To summarize, we presented a model with vector-like leptons that accounts for both neutrino masses and dark matter, and is consistent with the relic density and all direct and indirect searches. Assuming a single dark matter particle, the experimental data restricts the DM candidate to be light: in the 37-52 GeV, or 57-63 GeV range, or heavier than 95 GeV, all for points satisfying relic density constraints. In addition, the neutrino flux excludes DM particles with mass in the 74-85 GeV range.

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